Artificially Structured Materials for HEP Detector Applications

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What are Meta-materials?

Meta-materials are fabricated structures and composite materials that either mimic known material responses or qualitatively have new, physically realizable response functions that do not occur or may not be readily available in nature $\rightarrow$ artificially structured materials that have a certain impact on any kind of waves

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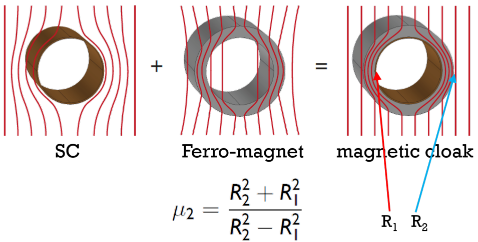
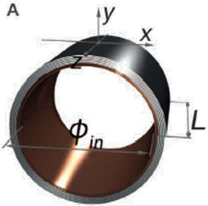


$$\mu_2 = \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2}$$

Fedor Gömöry *et al.*, *Science* **335**, 1466 (2012), DOI: 10.1126/science.1218316

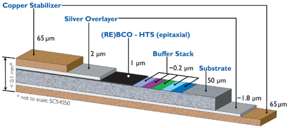


SC tape @ R_1: ReBCO (cuprate HT-SC)

FM-tape @ R_1 to R_2: $Fe_{18}Cr_9Ni$ $\mu_2 = 3.54$

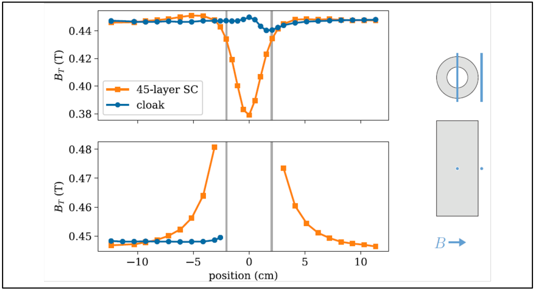
manufacturing FM with customized μ_r dependent on fractional mass f_m

manufacturing SC with ReBCO "tape"

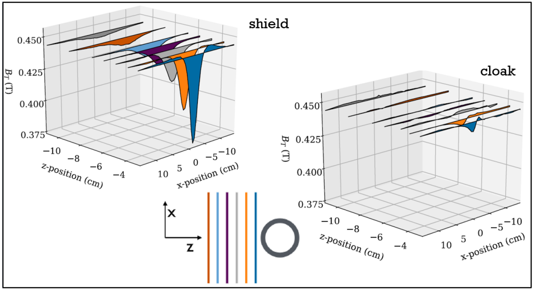


Meta-materials Example: Magnetic Cloak

4.5 inches long -- 45-layer SC shield/cloak(μ_r=2.43)



μ_r effectively reduced due to higher fields



Transformation Optics TO

The realization of meta-materials is an ongoing endeavour.

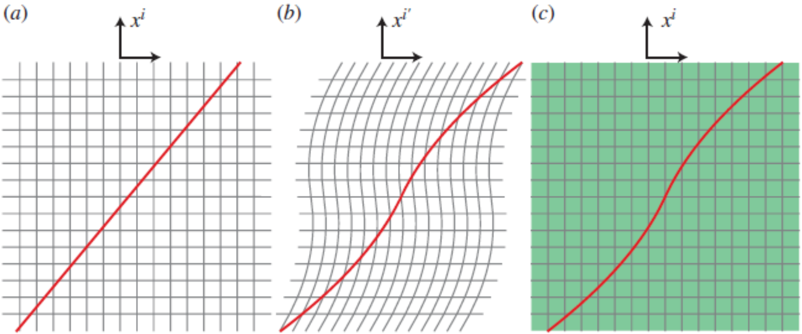
Transformation optics may be one of the tools to realize meta-materials.

- ♢ Spatially changing refractive index leads to changes in light-(EMF) propagation characteristics, for instance → MIRAGE
- ♢ Artificial media that have spatially changing optical properties can bend light in almost any manner
- ♢ Manipulate optical properties → Transformation Optics
  - ⋆ Framework exploiting form-invariance of Maxwell's equations in design of material parameters of optical devices
  - ⋆ Form-invariance of Maxwell's equations under coordinate transformations → equivalence between geometries and media
- ♢ Trustingly meta-materials will do the job → TOM

TOM's Physical and Electromagnetic Space

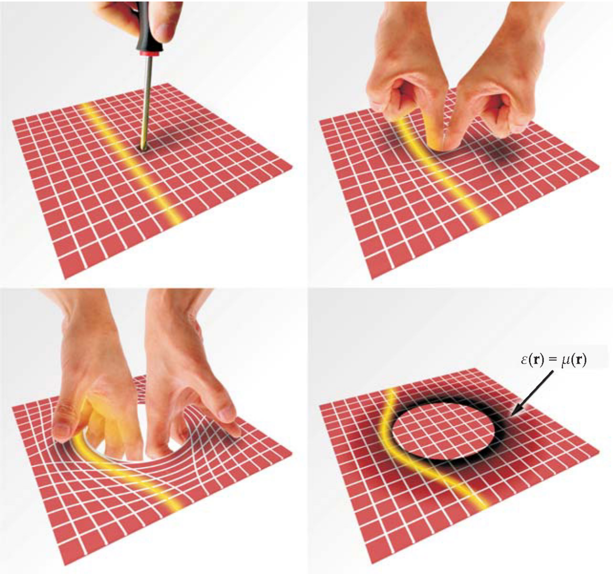
- Equivalence between geometries (Electromagnetic Space **EM**) and media (Physical Space **PH**)

TOM Principle



(a) **EM** in Cartesian coordinate system
(b) Same **EM** in deformed coordinate system x′ $= f(x, y)$; y′=y
(c) **PH**, in which meta-material is implemented as of curved **EM** (b)

TOM's Physical and Electromagnetic Space



Wegner, Linden, Physics Today, Oct. 01, 2010

Cherenkov Photon Manipulation [1]

- Sought after properties: material parameters of medium for Cherenkov radiation along x-axis in medium with background refractive index $\varepsilon_b = n_b^2$, with *linear coordinate stretching* along principle axes: $x' = f(x), y' = g(y)$ and $z' = h(z)$
- Equivalence relation of transformation optics yields material properties

$$\frac{\varepsilon_{x,x}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{x,x}}{\mu_0} = \frac{g'(y)h'(z)}{f'(x)}$$

$$\frac{\varepsilon_{y,y}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{y,y}}{\mu_0} = \frac{f'(x)h'(z)}{g'(y)}$$

$$\frac{\varepsilon_{z,z}}{\varepsilon_0\varepsilon_b} = \frac{\mu_{z,z}}{\mu_0} = \frac{f'(x)g'(y)}{h'(z)}$$

with f', g', h' transformations into **PH**

(1) Ginis V. et al. "Controlling Cherenkov Radiation with Transformation-Optical Metamaterials". In: *Physical Review Letters* 113.167402 (2014). DOI: 10.1103/PhysRevLett.113.167402.

Cherenkov Photon Manipulation

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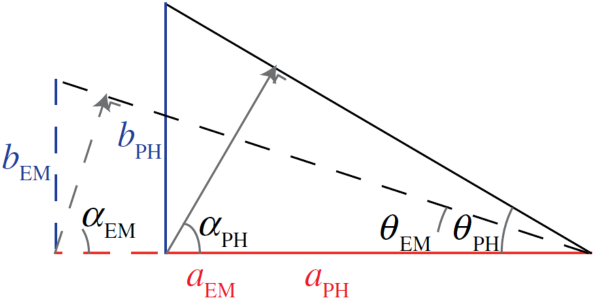
- Cherenkov radiation obeys geometry of electromagnetic reality
- Cherenkov cone can be manipulated with material parameters $\rightarrow$ coordinate transformations
- Inhomogeneous Maxwell equations with plane monochromatic wave as solution yields dispersion relation $\rightarrow$ calculate Cherenkov angle in TOM



- Resultant [2]:

$$\tan(\alpha_{PH}) = \frac{k_y}{k_x} = \frac{G}{F}\frac{\sqrt{F^2\epsilon_b\omega^2/c^2 - k_x^2}}{k_x} = \frac{G}{F}\tan\left(\theta_{Ch,(Fn_b)}\right)$$

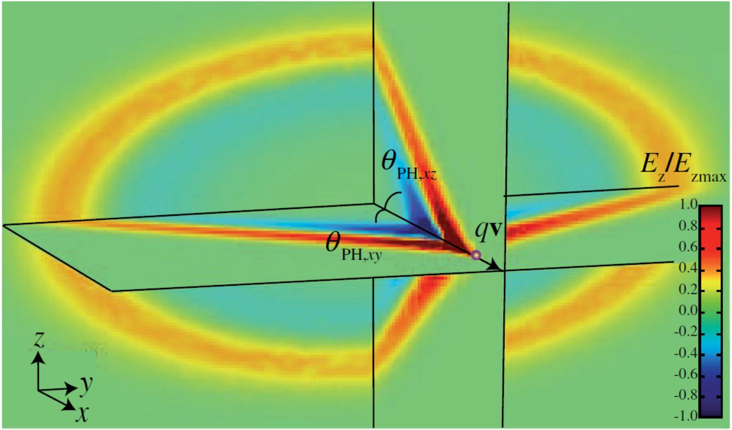
$\theta_{Ch,(Fn_b)}$: angle of Cherenkov radiation emitted in a medium with refractive index Fn_b

Compare to classical Cherenkov angle:

$\theta_{Ch} = \arccos\left(\frac{1}{n\beta}\right)$ vs. $\theta_{Ch,n_b} = \arccos\left(\frac{1}{Fn_b\beta}\right)$

[2] $F = f',\ G = g',\ H = h'$

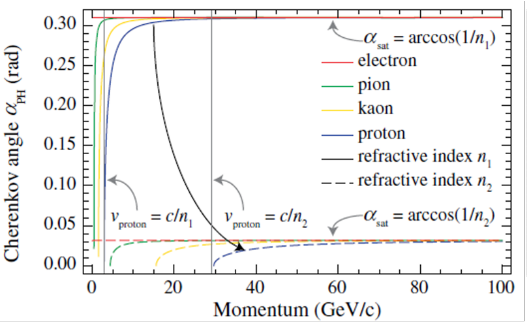
Cherenkov Photon Manipulation

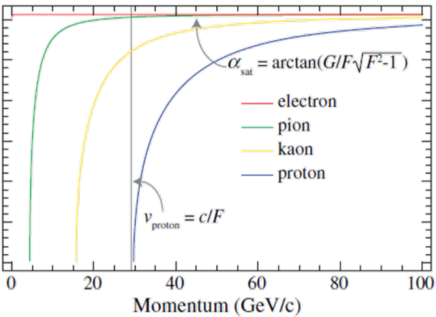


Anisotropic *TOM* medium: background medium implements coordinate transformation

$$n_b = 3,\ F = 0.7,\ G = 0.5,\ \text{and}\ H = 1$$

Cherenkov Photon Manipulation





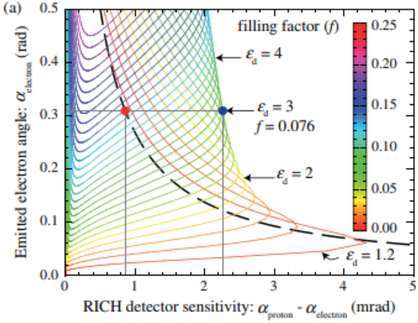
Aerogel vs CF_4

"Meta-CF_4"

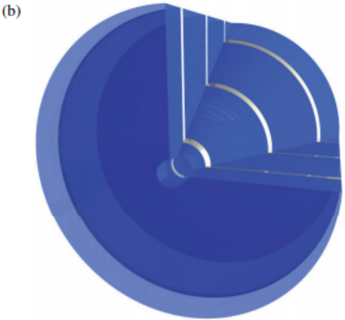
$F = 1.0005 \quad G = 10$

Meta-Materials for Cherenkov-Radiation Detection

- Design and fabricate devices providing materials with inhomogeneous indices of refraction

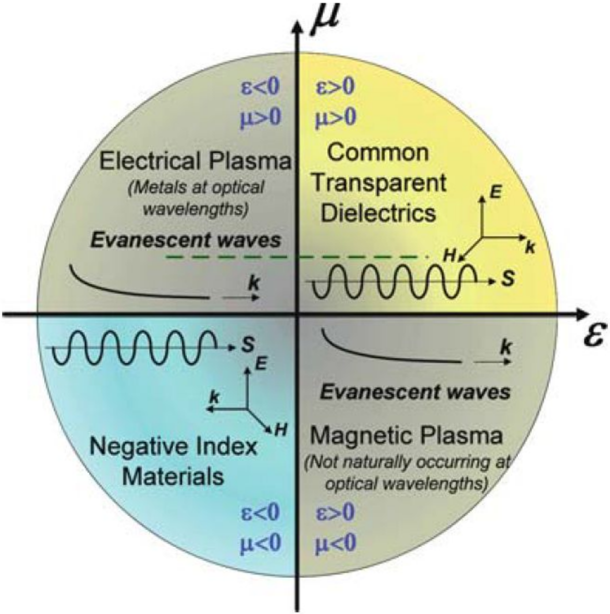


Comparison between traditional radiators and meta-material radiators for fixed momentum (40 GeV/c) and wavelength ($\lambda = 700\ nm$)



Implementation of meta-material: Several thin silver cylinders embedded in a dielectric with $f = 0.076$

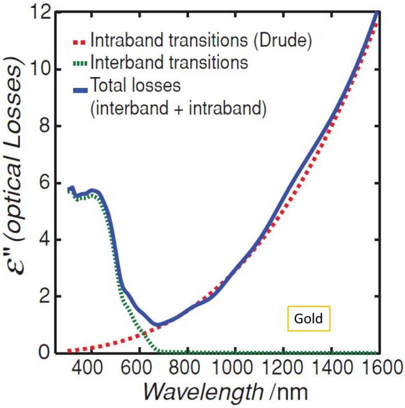
Challenges

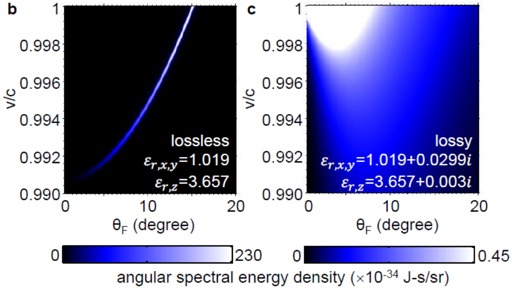


μ
ε
ε<0
μ>0
Electrical Plasma
(Metals at optical wavelengths)
Evanescent waves
ε>0
μ>0
Common Transparent Dielectrics
E
k
H
S
S
E
k
H
Negative Index Materials
ε<0
μ<0
k
Evanescent waves
Magnetic Plasma
(Not naturally occurring at optical wavelengths)
ε>0
μ<0

Challenges

- Design a *di-electric* with $f = 0.076$
- Di-electric constant ε contains real ε' and imaginary component ε'' $\rightarrow$ so does n: $n = n' + in''$
- Silver is a metal $\rightarrow$ non-transparent to visible light





Possible Workaround: Condensed Matter Problems

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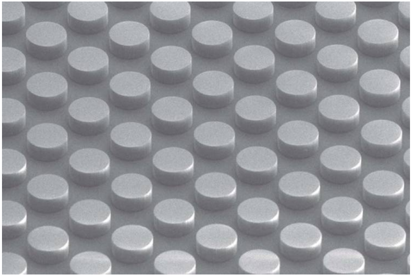
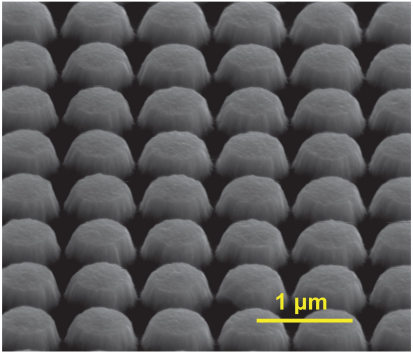
- Use of alkali metals $\rightarrow$ transparent in the UV
- Plasmons
- Design of metal-like materials using unconventional materials
- Carrier concentration manipulation
- Local variation in rod structure regarding filling fraction/thickness/pitch
- Arrangement of shells of spherical nano-particles
- Nanowires
- Sub-wavelength hole arrays
- ...

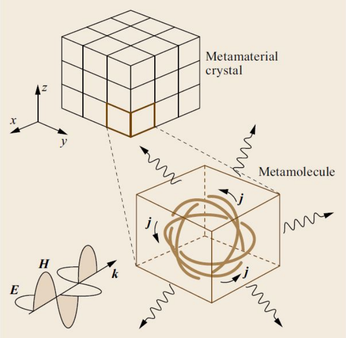
... a combination thereof.

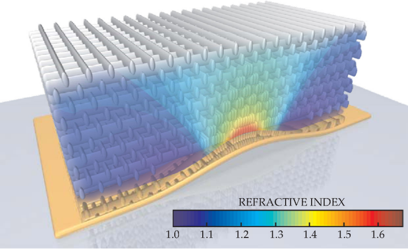
Let AI determine the right combination(s).

Possible Workaround: Condensed Matter Problems









Cornucopia MIRaGE from Sandia Labs

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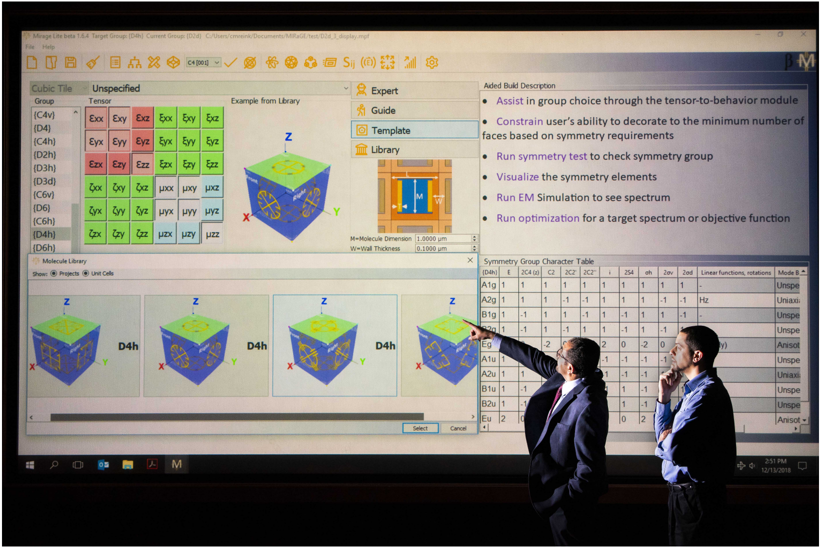
MIRaGE

Multiscale Inverse Rapid Group-theory for Engineered-metamaterials



Cornucopia MIRaGE from Sandia Labs

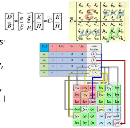
MIRaGE

Multiscale Inverse Rapid Group-theory for Engineered-metamaterials

Templated Build

- User is assisted in group choice through the tensor-to-behavior module
- User's ability to decorate will be constrained to the minimum number of faces based on symmetry requirements
- Symmetry test is run to check symmetry group
- Symmetry elements are visualized

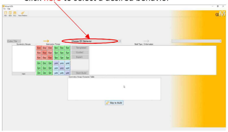
Tensor-to-behavior explanation



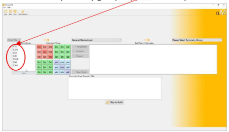
- Mapping:
- Molecular oscillations · Electric currents
- Linear vibrations: *x*, *y*, Electric field E_x, E_y, E_z
- Axial rotations: R_x, R_y, Magnetic field H_x, H_y, I
- **Unlimited Access to Tensor Elements!**

Tensor choice

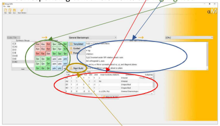
- Click here to select a desired behavior



- Possible symmetry groups appear that fit your choice



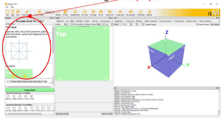
- Character table for your choice (e.g. C_{4v}) is displayed…
- Click "**Templated**"; build overview is shown
- Corresponding tensor elements are highlighted



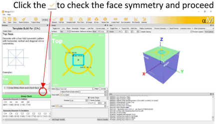
- Alternatively, tensor elements can be chosen first, instead of general behavior
- Click "**Start Build**" to proceed!

Meta atom/molecule design

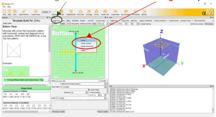
- Instructions for drawing are displayed



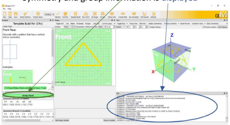
- You can draw lines, ellipses, and rectangles
- Click the ✓ to check the face symmetry and proceed



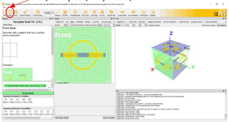
- Draw elements on the other specified faces
- Use visual grids and automated centering to help



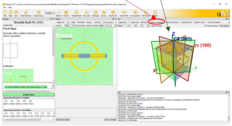
- Once decorations are done and face symmetry check validated, click "**Group Check**"
- Symmetry and group information is displayed



- …Or click "**Open**" and load a complete example from "data\examples\templated\"

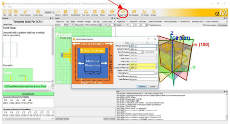


- Click "**Display Symmetries**" to visualize symmetry elements

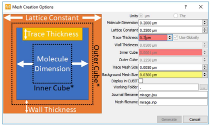


Meshing the design

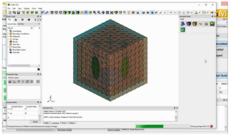
- Click "**Create Mesh**" to mesh your design in preparation for running FEM simulations



- Mesh Creation Options window appears
  - Yellow highlighted boxes indicate values that may cause meshin; SAND2018-3658D
  - Red highlighted boxes indicate values that are invalid

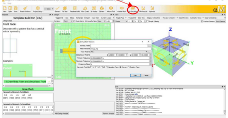


- CUBIT opens and meshes the cube

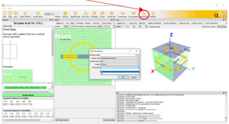


Running FEM simulation

- Click "**Run Simulation**" to start the FEM simulation



- Click "**Plot Results**" to visualize simulation results



Conclusion

- Transformation optics as theoretical framework allows to design any optical configuration
- Realization through meta-materials
- Possibilities for implementation in HEP detectors
- Exciting prospects

But

- Large parameter space to scan through
- A variety of challenges to tackle

But

- Tools are available $\rightarrow$ when?

Supporting material

Some Notes on E'n'M and Cherenkov Radiation

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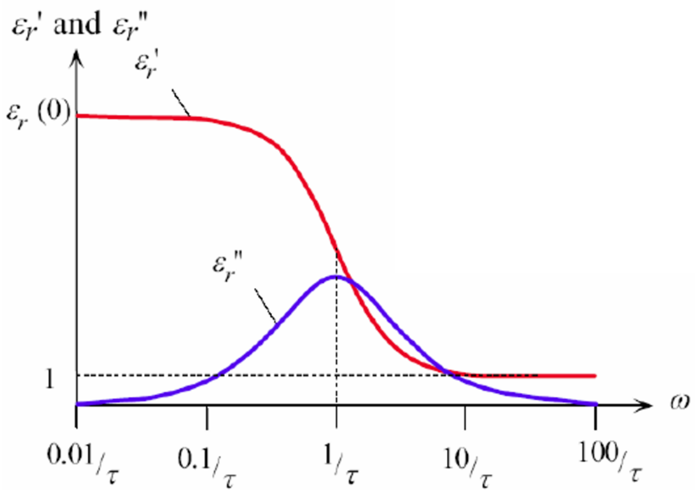
- Refractive index of a material $n \rightarrow$ defined as ratio of speed of light in vacuum to speed of light in material $n = \frac{c}{c_{\mathrm{m}}}$ (c: speed of light in vacuum, c_{m}: speed of light in material)
- With Maxwell's equations one can derive (electric permittivity ε and magnetic permeability μ)
  - $c = 1/\sqrt{\mu_0 \varepsilon_0}$, and similar: $c_m = 1/\sqrt{\mu\varepsilon}$
  - For non-magnetic material: $c_m = 1\sqrt{\mu_0 \varepsilon}$
  - $n = \sqrt{\mu_0 \varepsilon}/\sqrt{\mu_0 \varepsilon_0} = \sqrt{\varepsilon/\varepsilon_0} = \sqrt{\varepsilon_r}$
  - Permittivity: $\kappa = \frac{\varepsilon}{\varepsilon_0} = n^2$

In general: complex formulations and frequency dependent

- $\varepsilon_r(\omega) = \varepsilon_r'(\omega) + i \cdot \varepsilon_r''(\omega)$
- $n^*(\omega) = n(\omega) + i\kappa(\omega)$, here κ is the extinction/attenuation coefficient, NOT relative permittivity
- $[n(\omega) + i\kappa(\omega)]^2 = \varepsilon_r'(\omega) + i \cdot \varepsilon_r''(\omega)$
- $n = \sqrt{1/2\left(\sqrt{\varepsilon'^2 + \varepsilon''^2} + \varepsilon'\right)}$, $\kappa = \sqrt{1/2\left(\sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon'\right)}$

Polarization Response



Cherenkov Luminescence

- 1888: Oliver Heaviside predicted luminescence from particles traveling faster than c_m
- 1934: Pavel Cherenkov observed luminescence
- 1937: Ilya Frank and Igor Tamm developed theory behind Cherenkov's observation

Displacement of electrons in atoms in traversed medium, subsequent relaxation

Relaxation results in emission of photons, Huygens–Fresnel principle $\rightarrow$ coherent radiation if $v_{part} > c_m$

Mechanism of Vavilov-Cherenkov Radiation

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Case: Motion with $\mathrm{v}_{particle} = v < c_m$

- Charge moving in medium with $v/c_{m,phase} < 1$ [3] $\rightarrow$ Coulomb field in point M at some distance r_0 from charge trajectory
- Does not ionize medium's constituents!
- Medium provides symmetry $\rightarrow$ energy transfer "all around" and does not change trajectory of charged particle
- Couplings of electrons with nuclei not disturbed $\rightarrow$ medium returns to outgoing particle energy spent for polarization in accordance with Newton's Second Law
- Processes take place in all points situated symmetrically relative to particle's trajectory $\rightarrow$ radiation does not arise

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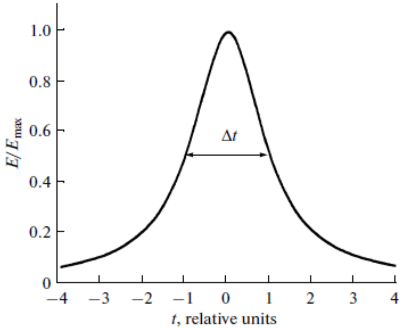
[3] $v/c_{m,phase} = \beta_m$ can be > 1

Coulomb-field at M with $\vec{r}$ relative to particle's position

$$\vec{E} = \frac{e\vec{r}}{4\pi\varepsilon r^3}$$



Variation of modulus of electric field intensity at point M when $v_{particle} < c_{m,phase}$

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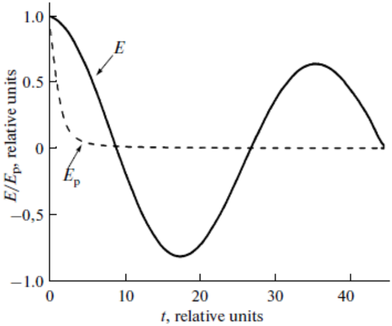
Case: Motion with $v > c_{m,phase}$

- $\vec{E} = \frac{e\vec{r}\left(1-\beta^2\right)}{4\pi\varepsilon r^3\left(1-\beta^2\sin^2\phi\right)^{3/2}}$



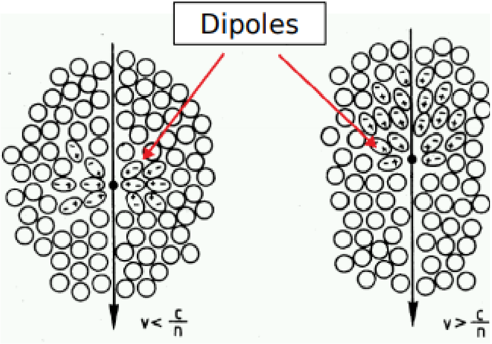
Variation of modulus of electric field intensity at point M when $v_{particle} > c_{m,phase}$

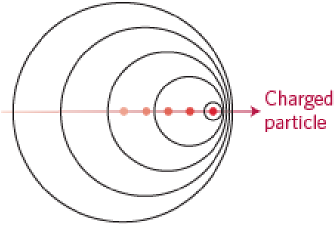
Mechanism of Vavilov-Cherenkov Radiation

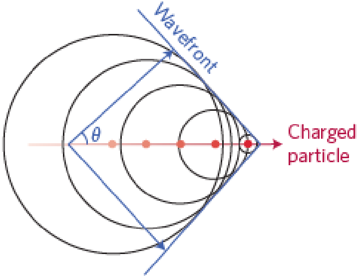
Cherenkov effect occurs because

- Motion with $v > c_{m,phase}$
- Rate of decay of electric field caused by outgoing particle exceeds rate of field variation of quasi-elastic dipole
- Interaction of polarized atoms between one another does not allow the wave to follow quick variation of electric field of moving charge
- Freely oscillating quasi-elastic dipoles radiate energy that they received $\rightarrow$ conservation of energy

Cherenkov Luminescence







Cherenkov Luminescence

(1) Radiation observed at angle of $\cos\theta = 1/(\beta n)$ only

(2) Radiation vanishes when $v < \beta = 1/n$

(3) Radiation intensity linearly depends on thickness of radiator

(4) Radiation completely linearly polarized $\rightarrow \frac{\vec{E}}{E}$ in plane of particle trajectory and $\frac{\vec{r}}{r}$

(5) Spectrum determined by $\beta n > 1$

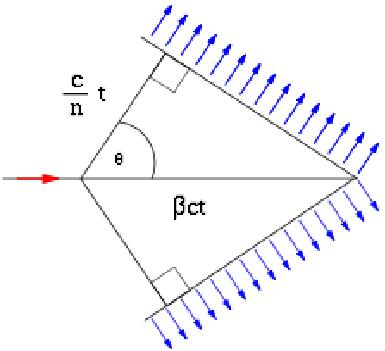
Cherenkov Luminescence

Cherenkov cone angle

- $x_{part} = v_{part} \cdot t = \beta c \cdot t$
- $x_{em} = v_{em} \cdot t = \frac{c}{n} \cdot t$
- $\cos\theta = \frac{c}{n} \cdot t/(\beta c \cdot t) = \frac{1}{n\beta}$
- $\theta = \arccos\left(\frac{1}{n\beta}\right)$

For 1-D meta-materials:

$$\cos\theta = \frac{1}{n\beta} + \frac{n}{k_0}\frac{d\phi}{dx}$$



Note: $n = n(\omega)$

Cherenkov Luminescence

Total amount of energy radiated per unit length

$$\left(\frac{dE}{dx}\right)_{rad} = \frac{z^2e^2}{c^2}\int_{\varepsilon(\omega)>\frac{1}{\beta^2}} \omega\left(1-\frac{1}{\beta^2\varepsilon(\omega)}\right)d\omega$$

- Integration over frequencies ω for which $v_{part} > \frac{c}{n(\omega)}$
- Cherenkov radiation is continuous
- Cutoff frequency above which intensity cannot increase $\rightarrow n = n(\omega)$ and out-of-phase relation of driving and radiated em-waves

Photon flux:

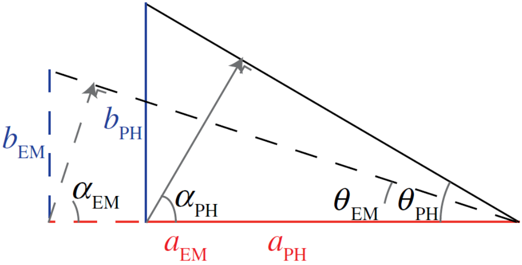
$$\frac{dN}{dx} = 2\pi\alpha\left(1-\frac{1}{(\beta n)^2}\right)\int_{\lambda_1}^{\lambda_2}\frac{1}{\lambda^2}d\lambda = 2\pi\alpha\sin^2\theta\int_{\lambda_1}^{\lambda_2}\frac{1}{\lambda^2}d\lambda$$

This yields

$$\frac{dN}{dx} = 2\pi\alpha\sin^2\theta\frac{1}{\lambda_1} \text{ for } \lambda_2\rightarrow\infty$$

Cherenkov Photon Manipulation

Stony Brook University

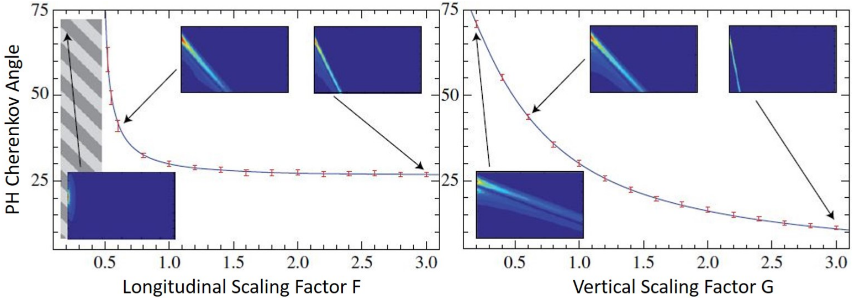


- Particle seems to be traveling with velocity Fv in **EM**, in a medium of refractive index n_b, emits photons with $\theta_{\textbf{EM}} = \arcsin\left(\frac{c}{n_b F v}\right)$
- For getting into **PH**: coordinates $x,\ y$ need to be compressed by $F,\ G$ in **EM**
- In **PH**: $\theta_{\mathrm{PH}} = \arctan\left(\frac{F}{G}\tan\left(\arcsin\left(\frac{c}{n_b F v}\right)\right)\right)$ (4)

(4) Analogously, the x-z-plane would need the factor $\frac{F}{G}$ replaced by $\frac{F}{H}$.

Full-wave numerical simulations of Cherenkov radiation

$$c/(n_b v) = 0.5$$



$G = 1$ $\quad$ $F = 1$